A high etendue spectrometer suitable for core CXRS on ITER[a)]

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A feasibility study for the use of core charge exchange recombination spectroscopy on ITER has shown that accurate measurements on the helium ash, the ion temperature and the plasma rotation require a spectrometer with a high etendue of $1mm^2sr$ to comply with the measurement requirements of ITER[1]. To this purpose such an instrument has been developed consisting of three separate wavelength channels (to measure simultaneously He/Be, C/Ne and H/D/T together with the Doppler shifted direct emission of the diagnostic neutral beam the BES signal), combining high dispersion (0.02 nm/pixel), sufficient resolution (0.2 nm), high efficiency (55%) and extended wavelength range (14 nm) at high etendue. The combined measurement of the beam emission (BES) along the same sightline within a third wavelength range provides the possibility for in-situ calibration of the CXRS signals. In addition to the three regular wavelength channels, the option is included to use the same instrument for measurements of the fast fluctuations of the beam emission intensity up to 2 MHz, with the aim to study MHD activity. This prototype instrument has been in operation at the TEXTOR tokamak, yielding absolute concentrations of impurity profiles, velocity and temperature profiles, information on the fast beam ions as well as fluctuation data on the BES.

I. CXRS ON ITER

Charge eXchange Recombination Spectroscopy (CXRS) is the standard technique in magnetic confinement experiments to determine profiles of ion temperature, plasma rotation and impurity densities. The fully ionized light elements will emit light upon a charge exchange reaction with the externally injected neutral beam. The accuracy of this local measurement depends on the photon statistics of the resulting spectrum: as a qualifier the signal-to-noise S/N can be used which has been derived to amount to[2]:

$$\frac{S}{N} = \frac{I_n c_\alpha \sigma_{cx} e^{-\int dr n_e \sum c_z \sigma_{z,stop}}}{8\pi^2 w_\perp \sin\alpha \sqrt{\pi Z_{eff} g_{ff} L_p B}} \sqrt{\Delta t \frac{\Delta\lambda \cdot \lambda_{de}}{\lambda_\alpha^2} \Re} \quad (1)$$

where the signal-to-noise-ratio $\frac{S}{N}$ is calculated to be the ratio of the CX-signal at the half width and the noise being the fluctuations in the bremsstrahlung background.The beam attenuation is taken into account by the cross section for ionization with an impurity z,$\sigma_{z,stop}$. Other parameters in eq. 1 represent c_α the concentration of the measured impurity, σ_{cx} the effective cross section for the observed CX reaction, I_n the neutral beam current, n_e the electron density, $w_\perp$ the beam width, Z_{eff} the effective ion charge, g_{ff} the Gaunt factor, L_p the integration length of the line of sight through the plasma and B the bremsstrahlung emissivity. The detection branch is taken care of in the last part of the equation: Δt the integration time, $\Delta\lambda$ the wavelength range, λ_α the CX transitional wavelength and λ_{de} the centre of the detected wavelength. The detection efficiency is given by $\Re = T \cdot \eta \cdot \Delta\Omega \cdot A_{spec}$, with T the overall transmission of the optical system, η the detector efficiency and $G = \Delta\Omega A_{spec}$, the product of acceptance angle and area is the etendue of the system.

The situation at the core of a fusion reactor is quite dramatic: the signal is low due to the large beam attentuation (for an ITER high performance discharge only about 1% of the injected neutral beam particles reach the plasma centre), whereas the noise originating from the background radiation (dominated by the bremsstrahlung) is an order of magnitude higher than in present fusion devices, due the longer integration length in combination with the high density. Therefore, in order to comply with the measurement requirements and

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TABLE I. Main requirements on the core CXRS diagnostic for ITER

Parameter	Accuracy	Time resolution	Radial resolution
Ion temperature T_i	10 %	100 ms	a/30
Impurity density: He, Be, C	20 %	100 ms	a/10
Plasma rotation v_{tor}	30 %	10 ms	a/30
Z_{eff} (line averaged)	20 %	10 ms	–

TABLE II. Main requirements on the spectrometer

Wavelength band	Spectral resolution	Spectral lines	Efficiency $\times$ etendue (incl. QE)
460.8 - 473.6 nm	0.2 nm	HeII, BeIV	0.24 mm^2sr
518.9 - 533.1 nm	0.2 nm	CVI, NeX, ArXVII	0.13 mm^2sr
649.0 - 663.0 nm	0.1 nm	H_α D_α (BES)	0.06 mm^2sr

compensate for those two effects, a high efficient optical system with a high etendue is required. A feasibility study for the ITER core CXRS system[3] pointed out that the spectrometer etendue should be at least $1mm^2sr$, to have a S/N of the order of 10. This value, in combination with the boundary conditions on the spectral wavelengths bands and resolutions, the transmission efficiencies and the time resolution, urged for a new dedicated design of such instrument.

II. THE CORE CXRS SPECTROMETER

A. Requirements for CXRS on ITER

The core CXRS diagnostic for ITER is meant to provide the profiles of the ion temperature, plasma rotation, helium and carbon content subject to the requirements as listed in Table I.

For the detection channel, this led to the following considerations:

- The detection channel should include a measurement of the beam density to be able to determine the impurity density, preferably at exactly the same location as the CXRS emission. Note that for large beam attenuation the error progagation in the calculation of the beam density from the stopping cross-sections is exponentially increasing, leading to intolerable inaccuracies. Therefore a measurement of the beam density (instead of a calculation) is required.

- At least three wavelengths bands should read out simultaneously: one for Carbon, one for Helium and Berylium and one for Hydrogen to be able to monitor the beam density.

- to be compatible with the time resolution requirement on v_{tor} and Z_{eff} the readout time of the system was set at 10 ms.

- the radial resolution is determined by the front optics and beam width and independent of the detection channel. Since the lowest intensity orginate from the plasma core, the etendue of the spectrometer will be chosen such to arrive at the required accuracy for one radial channel per spectometer. Further to the plasma edge, where the beam density is much higher, more radial positions can be imaged onto one instrument.

B. Requirements on Spectrometer

The considerations in the previous sections, in combination with the known CX lines used in present experiments, resulted in the spectral specifications of the three detected wavelength band of the spectrometer as listed in TableII. The origin of the efficiency etendue parameter lies in an analysis of which the results are given in Ref [[4]]. For the spectrometer this results in an etendue of 1.05 mm^2sr and an efficiency of 0.55 (0.92 for the transmission $\times$ 0.6 for thegrating efficiency).

Concerning the spectral resolution it was derived[5] that making the spectral resolution better than 0.2 nm for the HeII band would hardly improve the performance of the system. A requirement was set to be able to decrease the slit width thus allowing to verify the model by experiment.

C. Spectrometer Design

A number of high-level decisions have been made to design a spectrometer that provides the required large etendue within the other constraints. The first high-level design decision was to use a single grating for all three channels. The alternative would have been to build separate spectrometers for each channel, which would have resulted in a larger cost, since the grating is a major cost driver. Secondly, the grating size has been limited to a length of 200 mm. Although this complicates the optical design, it makes commercial procurement of the grating possible. This decision was based on experience from previous projects with similar spectrometers, in which grating availability proved to be a major cost and schedule risk.Thirdly, it was decided to base the design on commercially available sensors and not to anticipate on sensors with larger image areas that might become available in the future. A larger image area would have made the optical design significantly easier, the uncertainty of such future sensor development was considered too big a risk. Finally, CCD sensors have been selected, because they allow for binning of chip, which significantly reduces the readout noise. A vertical binning of up to 1024 pixels is foreseen for the spatial channels that are noise critical, which effectively reduces the contribution of readout noise by a factor 32.

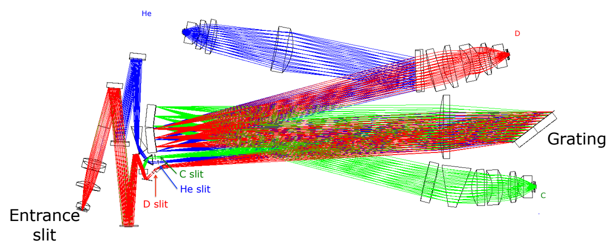

FIG. 1. Design of the high etendue, 3 channel spectrometer, using a single grating. The blue lines represenct the Helium channel, the green lines the Carbon channel and the Red lines the Hydrogen channel. In principle a fourth wavelength band can be added.

The design is engrafted on the design of the OMI (Ozone Monitoring Instrument) spectrometer, which is now monitoring the earths atmosphere from a NASA satellite as part of the Aura mission. Fig. 1 shows an overview of the design.

The light enters the spectrometer via a fiber bundle. This fiber bundle consists of 68 fibers with a core-diameter of 300 μm that are aligned in a single row. The first part of the spectrometer, which is called the front optics, has the function to split three wavelength ranges and to image each range onto a separate slit with a demagnification factor. The demagnification factor is needed to adapt the f-number from the fibers to the f-number required by the subsequent optics. In principle the design is suited to adapt a fourth wavelength band. By giving each spectral range its own slit, the spectral resolution of each channel can be set differently.

The front-optics is followed by a second part of the optics, which is the actual spectrometer. In the spectrometer, the light from the three slits is combined by a large collimator lens on a single grating. This grating has an active area of 100x200 mm^2 and 500 lines/mm. Although this grating is considerably smaller than gratings in competing designs, it still proved very costly to procure. The light coming from the grating travels back through the collimator to two field mirrors. The two mirrors provide a spatial separation between the carbon-channel, which is reflected downwards in Fig. 1, and the helium and BES channels, which are reflected upwards. The separation between the helium channel and BES channel is performed by a dichroic. For each channel, an $F/1$ objective is used to demagnify the image so that the spectral image fits onto the sensor (size: 13×13 μm^2, 1024x1024 pixels). Due to this low f-number, the sensor has to be positioned into the image plane.

The dispersion of the instruments amounts to about 1.5 nm/mm ($\sim 0.2\mathring{A}$/pixel), with some slight variation between the 3 channels. The spectra are recorded in the 5^{th}, 6^{th} and 7^{th} order for the different channels.

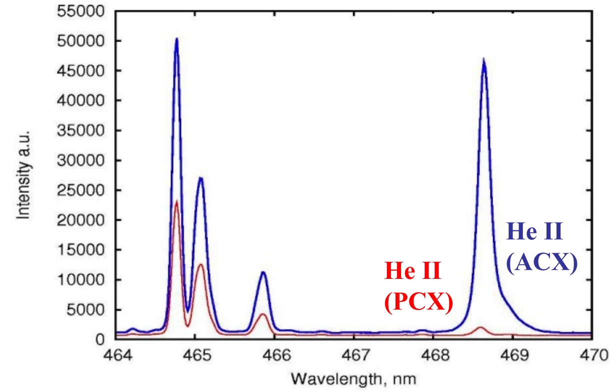

FIG. 2. Typical example of a helium spectrum as measured with the high etendue spectrometer on TEXTOR, in the case of passive emission only (PCX) and with the neutral beam switched, yielding the active charge exchange component (ACX).

III. PERFORMANCE CHARACTERISTICS

The prototype of the spectrometer has been built and put into operation at the TEXTOR tokamak for testing and has now been mounted on Asdex Upgrade. It has a modular design consisting of assemblies that can be replaced very accurately on the base plate. A minimum set of compensators is chosen and the limits of manufacturing accuracy are explored. The result is a stable spectrometer design that can be transported easily, aligned and re assembled with minor effort. Performance of the system is close to expectation. Typical examples of the helium ($HeII$ at 468 nm, $n = 4 \rightarrow 3$) and hydrogen (H_{alpha} at 656 nm) spectra are shown in Fig.2 and Fig. 3 respectively. Note that in these cases only 1/68 part of the spectrometer's etendue was used (68 radial channels where imaged on one spectrometer). Integration time was set at 40 ms, since the CCD detector was not able to read the 68 spectra out faster than 40 ms. A detector upgrade is ongoing to be able to record all spectra within the design specfication of 10 ms.

One of the goals of this spectrometer prototype was to determine the severity and impact of any ghost lines. Ghost lines are measured lines that originate from light with a wavelength outside of the intended wavelength range or orginating from one of the other two entrance slits. Ghost lines can, for instance, be caused by unwanted reflections on lens surfaces or by unwanted orders of the grating. All spectrometers suffer from ghost lines to some extent, so therefore it is important to establish how strong the ghost lines are and how they effect the measurements. Some ghost lines where observed initially on all three wavelenghts bands, but could be eliminated by a suitable filter after the entrance slit. At the H_α

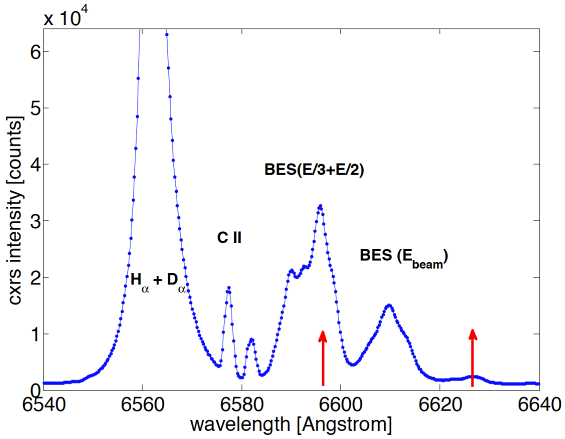

FIG. 3. Typical example of the hydrogen spectrum as measured with the high etendue spectrometer on TEXTOR. The CII emission from the plasma edge is visible as well as Doppler shifted beam emission of the three energy components. The red arrows indicate the positions of the ghost lines (the H_α emission entering from the other slits

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band however, still two lines can be recognized as seen in Fig. 3, which have been identified to be H_α light at a $< 1\%$ level of the other two slits. Measures are being taken to eliminated those as well.

IV. FLUCTUATIONS OF THE BEAM EMISSION

The main aim of the H_α band in the spectrometer is to determine the beam density. Alternatively the possibility to measure the fluctuations in the beam emission system (by flipping a mirror) has been integrated into the design. This allows to measure core MHD activity at 8 spatial channels sampled at 2 MHz. Pilot results on TEXTOR showed that the measurement fully confirmed the simulation results on achievable photon current at the detector and on the signal to noise ratio. Both fluctuation spectra as well as correlation spectra between teh channels could be obtained[8].

V. OUTLOOK

The results of this pilot spectrometer have shown that it is feasible to measure the CXRS emission at the required accuracy for ITER. For the final design a dedicated coating for each wavelength band will marginalize the effect of the ghost lines. The present detectors are well suited for a single channel readout, but will be replaced to be able to measure more (¿30) radial positions simultaneoulsy at a rate of 100 Hz or faster. The focus now will be to use the instrument at AUG for physics investigations like:
i) impurity investigations: combination of CX emission with beam emission allows absolute impurity profiles[6];
ii) fast ion investigations: the high etendue allows to focus on the wings of the spectra incorporating information on the energetic ions.[7];
iii) transport investigations: many radial channels should provide accurate profiles of ion temperature, plasma rotation and ion densities;
iv) MHD fluctuations: using the fast fluctuation BES measurement.

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